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Common Mode Radiation of a Printed Circuit Board with Embedded Decoupling Capacitor Excited by IC's Shoot-Through Current

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Abstract

Electromagnetic radiations of power bus with embedded decoupling capacitor composed of different insulator thicknesses were investigated for two cases: with on-board global capacitors and without them. In order to distinguish the common mode radiation of the power bus due to shoot-through current from normal mode radiation, two different lengths of signal traces were compared. It has been proved that radiated emission due to shoot-through current was reduced over the wide frequency range by the PCBs with thinner insulators without on-board global capacitors, and was reduced in the limited frequency range by the PCB with relatively thick insulator and on-board global capacitors.

Author(s) Biography

Toshio Sudo received the B.E., M.E., and Ph.D. degrees in electrical engineering from Tohoku University, Japan, in 1973, 1975, and 2006 respectively. He is currently a chief researcher in the Microelectronics Packaging Research Center, Corporate Manufacturing Engineering Center, Toshiba Corporation. His research interests include the electrical characterization and electromagnetic modeling of high-speed interconnects, and EMC design for LSIs and PCBs. Dr. Sudo is a member of the IEICE, JIEP, IMAPS, and the IEEE Fellow.

Seiju Ichijo received B.E. degrees in electronics engineering from Yamagata University, Japan in 1969. He joined Toshiba Corporation in 1969, where he has been engaged in the development of hardware design of various systems. He is an EMC engineer certificated by the NARTE. Mr. Ichijo is a member of the JIEP.

John Andresakis- Vice President of Strategic Technology for Oak-Mitsui Technologies has over 26 years experience in the manufacturing of Printed Circuit Boards. Before Oak-Mitsui, he was Engineering Manager for Hadco Corporation and was in Technical Management at Nelco, Digital Equipment and IBM. He holds a Masters Degree in Chemical Engineering from the University of Connecticut and a Bachelors of Engineering Degree from Cooper Union. He has received 8 patents related to PCB Production and is a member of the IPC Suppliers Technology Council and the various IPC committees developing specifications for Embedded Passives.

Kazuhiro Yamamzaki is currently the Marketing Manager for Oak-Mitsui Technologies. Before joining OMT, he was Technical Marketing Manager for Mitsui Mining and Smelting in Ageo,Japan in the area of Resin Coated Foil. He has a Masters Degree in Polymer Science from TOYOHASHI UNIVERSITY of TECHNOLOGY in Japan.

Introduction

Power bus structure in a high-speed printed circuit board (PCB) is an important design parameter for mitigating reference voltage fluctuation caused by the transient current flowing from/to active ICs [1]-[4]. Furthermore, the power bus structure affects radiated emission because it works as an unwanted antenna [5]. The power bus is ordinarily composed of two solid planes separated by dielectric insulator in a multilayer PCB. The insulator thickness determines the power supply impedance and effectiveness of the unwanted antenna.

Electromagnetic radiation of a PCB is roughly classified into two noise modes: "normal mode emission" caused by signal line excitation, the other is "common mode emission" excited by IC's power supply current. The former normal mode excitation is ordinarily accompanied by various types of secondary common modes.

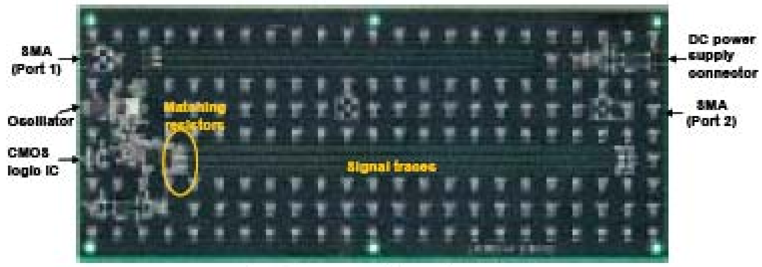
In this paper, 4-layer PCBs with embedded decoupling capacitors composed of different insulator thicknesses were investigated for two cases: without on-board global capacitors and with them. Ultra-thin dielectric insulator called FARADFLEX® was used for this purpose [6].

First, S parameters of the power bus structure were evaluated for the cases with and without on-board global capacitors. Next, far-field radiated emission associated with signal trace excitation was evaluated for the long signal traces. Then, in order to distinguish the common mode radiation associated with power bus structure, radiated emission was evaluated by exciting shoot-through current of IC for the case with short signal trace length. Thirdly, voltage fluctuations were measured in a whole area of the PCB for the cases with different embedded capacitors.

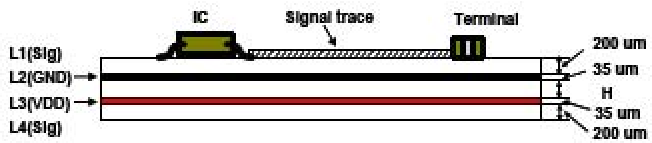
Board Configuration

Fig.1 shows an external appearance and a cross-section of the evaluation board. The board consisted of 4 conductive layers, whose size was 230 mm by 100 mm. The 1st and 4th conductive layers were assigned to be signal layers, the 2nd one was assigned to be the ground plane, and the 3rd one was assigned to be the power plane. The insulator thickness between the 2nd and the 3rd planes was varied 200, 100, 50, 16, 8 microns to examine the effect of the power supply impedance of the power bus as shown in Table 1.

A standard CMOS logic IC (TC74VCX 245FT) with 8 output buffer circuits was mounted on a PCB. Then 6 of the output bufferswere connected to the signal traces and operated at 10 MHz as a noise generator. Two different lengths of signal traces were examined to distinguish the effects of the common mode excitation of power bus by shoot-through current from normal mode radiation. The signal lengths were approximately 180 mm for the long trace and 5mm for the short traces as shown in Fig.2.



(a)Front side view



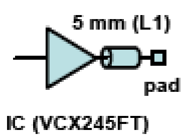
(b) Cross-sectional view

Fig.1 Board configuration

Table 1 Dielectric Thicknesses for Embedded capacitors

	Dielectric thickness (H)	Dielectric constant(Er)
FR4-200	200	4.4
FR4-100	100	4.4
FR4-50	50	4.4
BC16	16	4.4
BC8	8	4.4
BC16T	16	30

(a) Long trace



(b) Short trace

Fig.2 Two different lengths of signal routings

The characteristic impedance of the signal traces was approximately 70 ohms and 56-ohm chip resister was inserted as a source termination at the pad between 5-mm trace and 175-mm trace for the case of the long signal trace. Radiated emission is considered to be mainly excited by shoot-through current in the case of the short signal trace as shown in Fig.3.

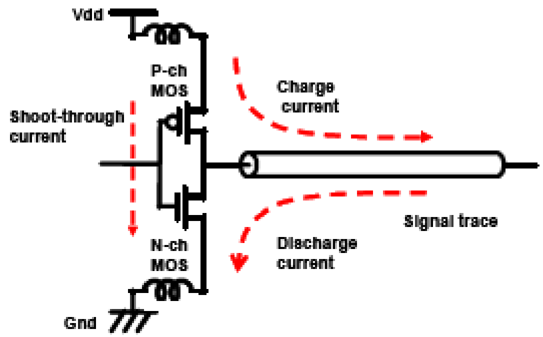
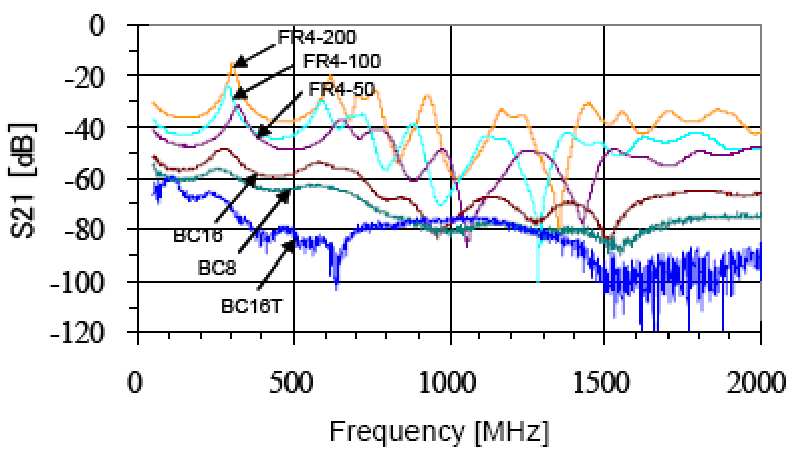


Fig.3 Excitation by a CMOS buffer circuit

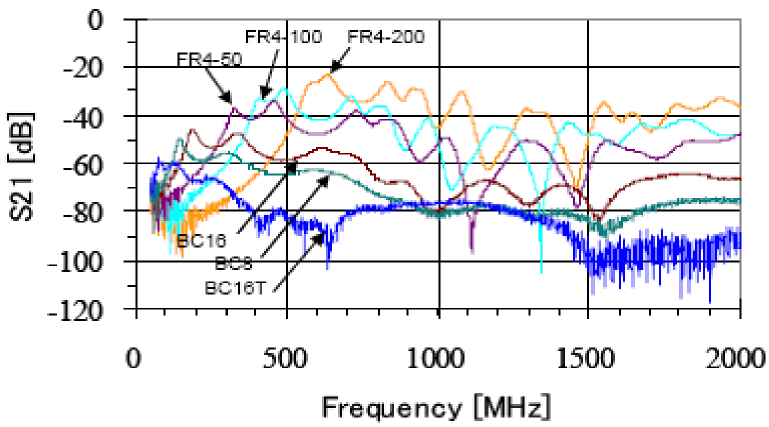
Two types of assembled boards were prepared: with on-board global capacitors placed with a regular spacing of 20 mm on the backside of PCB and without these on-board global capacitors. A total of 55 chip capacitors of 0.1 uF were mounted as global capacitors. In addition, local capacitors were mounted to stabilize logic operation for measuring EMI and power/ground bounce.

Experimental Results

S Parameters of Power Bus: First, S parameters (S21) of the PCB were measured for the different insulator thicknesses between two SMA connectors on the power/ground planes. Fig.4(a) shows S21 properties for the case without any on-board capacitors. Fig.4(b) shows the ones for the case with just on-board global capacitors.



(a) without any on-board capacitors



(b) with on-board global capacitors

Fig.4 Measured S21 properties of power/ground plane with different insulator thickness

It has been found that the S21 values of the PCB with thinner insulator became lower over the wide frequency range without on-board global capacitors. On the other hand, global capacitors made S21 value extremely low from DC to a certain frequency. Contrary to the expectation, this frequency region with low S21value became broader for the PCB with thicker insulator.

Fig.5 shows S21 properties of power/ground plane for the insulator thickness of 200 um. Fig.6 shows a lumped circuit model for the power/ground plane with on-board capacitors on the PCB. The f_o shows a fundamental resonant frequency of the plate, the f_a shows a parallel resonance composed of plate capacitance and local capacitors, and the $f_{(m,n)}$ shows membrane resonances of the plate. Here, the integer mode number is depicted in (m,n) to the x-, ydirections of the board, respectively. When just local capacitors were mounted around an IC driver and an oscillator before mounting onboard global capacitors, a parallel resonance f_a became prominent as shown in Fig.5.

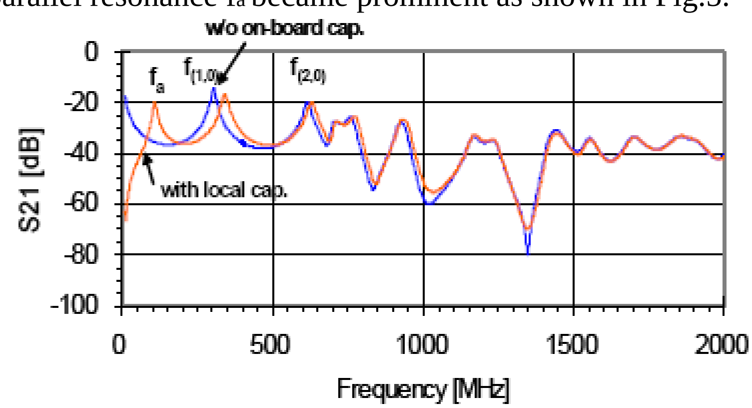
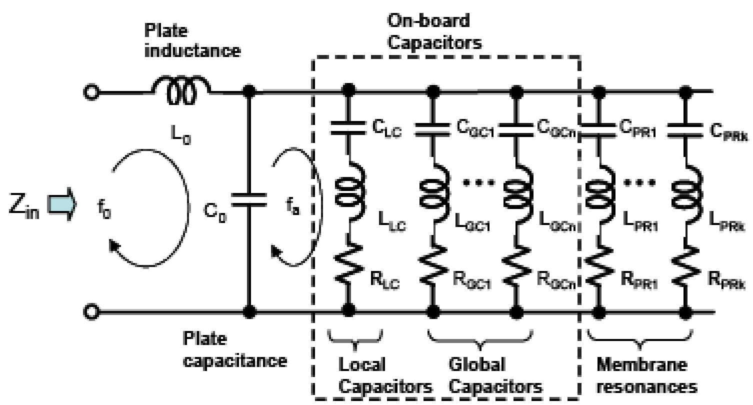


Fig.5 Measured S21 properties with on-board local capacitors around an IC driver



$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{L_0 C_0}}$$

$$f_a = \frac{1}{2\pi}\frac{1}{\sqrt{L_{LC}(C_0 + C_{LC})}}$$

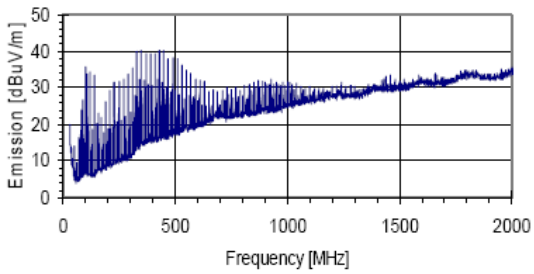
$$f_{(m,n)} = \frac{\nu_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

Fig.6 Lumped circuit model for input impedance of the power/ground plane

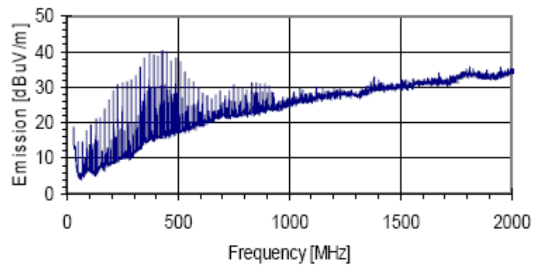
Far-field radiated emission: Next, the far-field radiated emission was measured with a distance of 3 m in a full anechoic room. Fig.7 shows measured radiated emissions for two different insulator thicknesses excited by long signal traces. Fig.7(a) shows the case of 200um thickness and Fig.7(b) shows the case of 8 um thickness. In these cases, no global capacitors were mounted and just local capacitors were mounted around the IC. Fig.8 shows the ratio between the two thicknesses. High reduction of radiated emission was observed at the frequencies corresponding to the resonant frequencies in Fig.5 without on-board global capacitors. In particular, even order harmonics were dramatically educed. As shown in Fig.7, however, normal mode radiation cannot be reduced even in the case of 8um.

Fig.9 shows measured radiated emissions for two different thicknesses excited by short signal lines, i.e. shoot-through current. In this case, no on-board global capacitors were mounted, and just local capacitors were mounted on the board.

Fig.10 shows the ratio of measured radiated emissions between two insulator thicknesses excited by short signal traces. It has been proved that common mode radiation due to shoot through current was significantly reduced by the power bus structure with thinner insulator without on-board global capacitors. In particular, radiated emission around 120 MHz corresponding to parallel resonant frequency can be remarkably reduced. In the cases of BC16 and BC16T, a similar level of reduction of radiated emission was observed.



(a) H=200 um



(b) H=8 um

Fig.7 Measured radiated emissions for two different insulator thicknesses with local capacitors excited by long signal traces

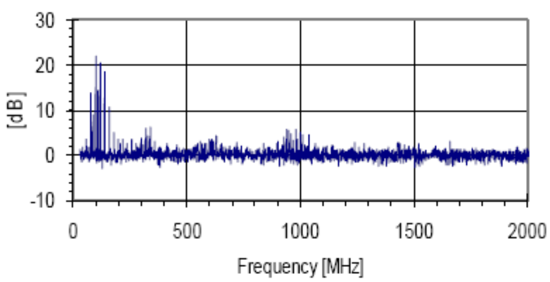
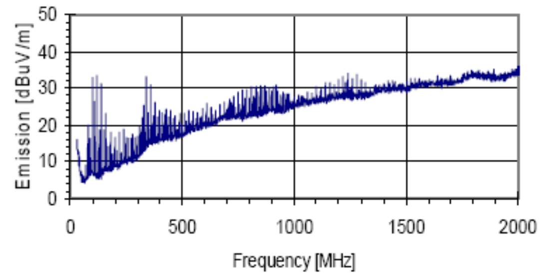
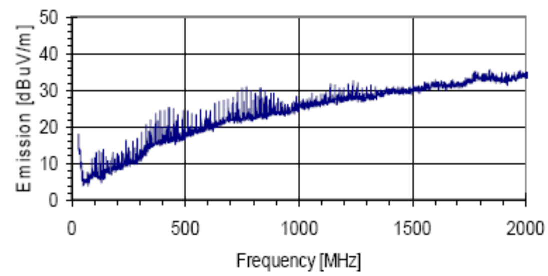


Fig.8 Ratio of measured radiated emissions for two different insulator thicknesses with local capacitors excited by long signal traces



(a) H=200 um



(b) H=8 um

Fig.9 Measured radiated emissions for two different thicknesses with local capacitors excited by short signal traces, i.e. shoot-through current

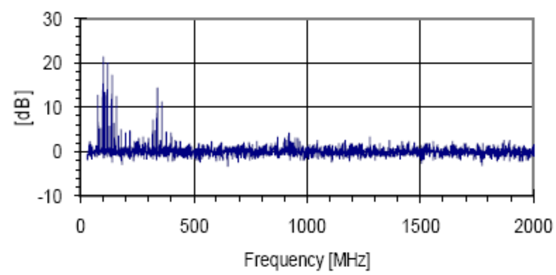


Fig.10 Ratio of measured radiated emissions for two different insulator thicknesses with local capacitors excited by short signal traces

Fig.11 shows measured radiated emission excited by long signal traces for the insulator thicknesses of 200 um with on-board global capacitors together with local capacitors. Fig.12 shows the ratio of radiated emission between with and without global capacitors for the insulator of thickness of 200 um. It has been found that radiated emission can be reduced by the on-board global capacitors without embedded decoupling capacitors to some frequency range corresponding to the low S21 region as shown in Fig.4(b).

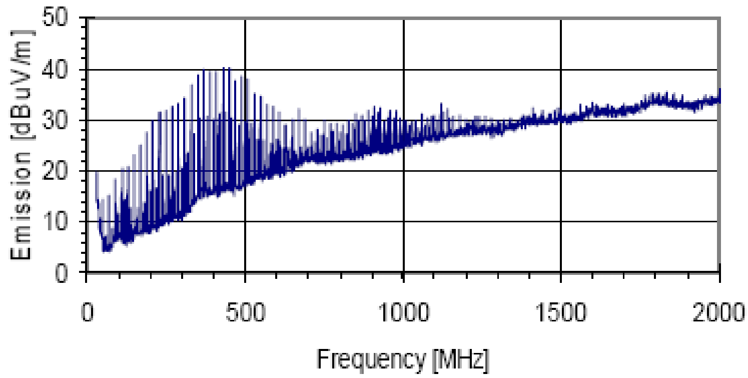


Fig.11 Measured radiated emissions for the insulator thicknesses of 200 um with on-board global capacitors excited by long signal traces

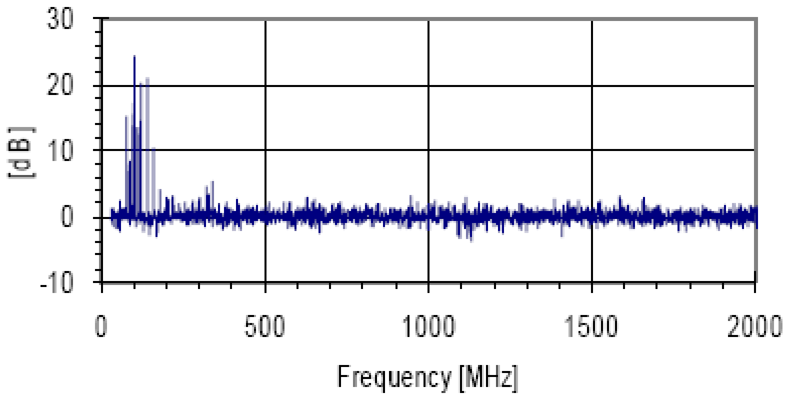
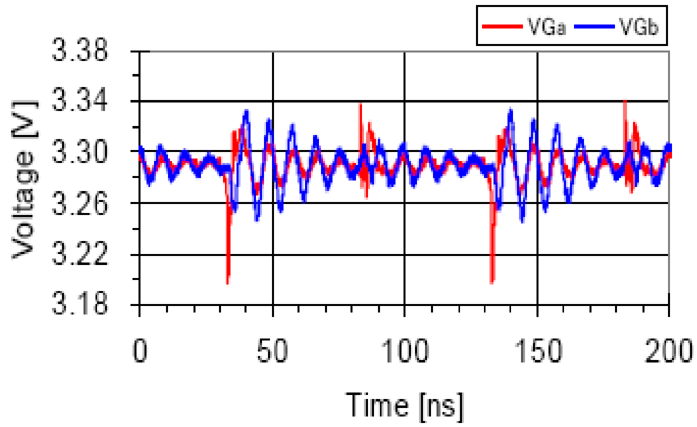


Fig.12 Ratio of measured radiated emissions between without and with global capacitors for the insulator thicknesses of 200 um excited by long signal traces

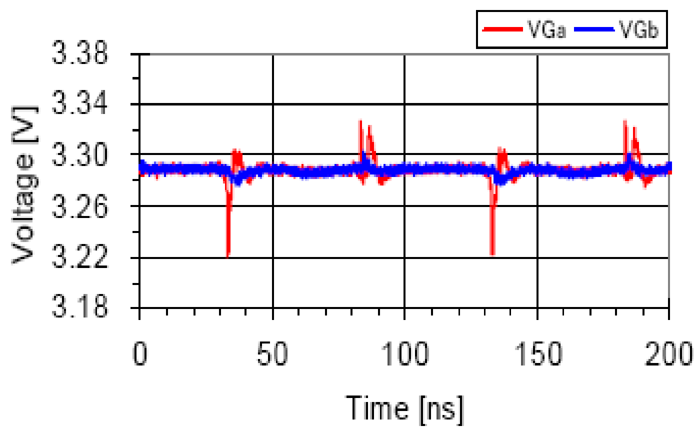
Bounce betweenPower and Ground Planes: Fig.13 shows measured voltage waveforms between power and ground planes for two insulator thicknesses. The waveforms were measured using an oscilloscope (HP54570A) and monitored at two points on the board. One was measured at the nearest point (VG_a) of IC.
The other was measured at the power supply terminal (VG_b) placed at the far edge of the board. The ringing waveform observed at VGb in Fig.13(a) was around 120 MHz and it corresponded to the parallel resonance f_a of the power bus.

Fig.14 shows measured power/ground bounce distribution in a whole board area. Fig.14(a) shows it for the case of 200 um insulator thickness without global capacitors, Fig.14(b) shows it for the case of 8 um without global capacitors, and Fig.14(c) shows it for the case of 200 um with global capacitors. The xi, yi shows measuring coordinates of the whole board. Thin insulator was found to be slightly more effective for reducing the power/ground bounce than global capacitors.

Fig.15 shows power/ground bounce distribution measured at the first membrane resonant frequency f(1,0), i.e. 340 MHz using a spectrum analyzer (Agilent4440A). Typical resonant distribution observed was shown in Fig.15.

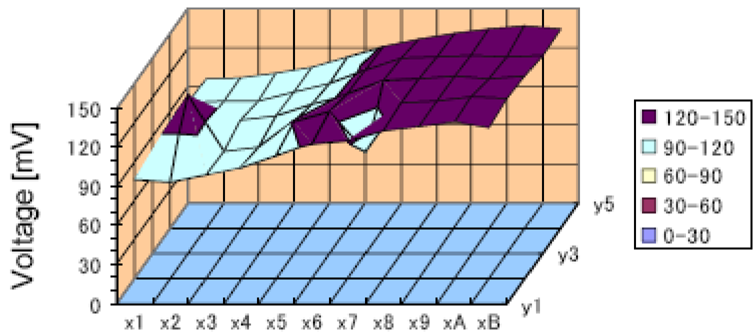


(a) H=200 um without global capacitors

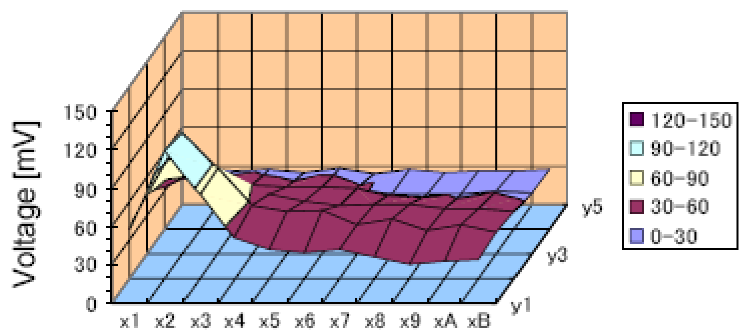


(b) H=8um without global capacitors

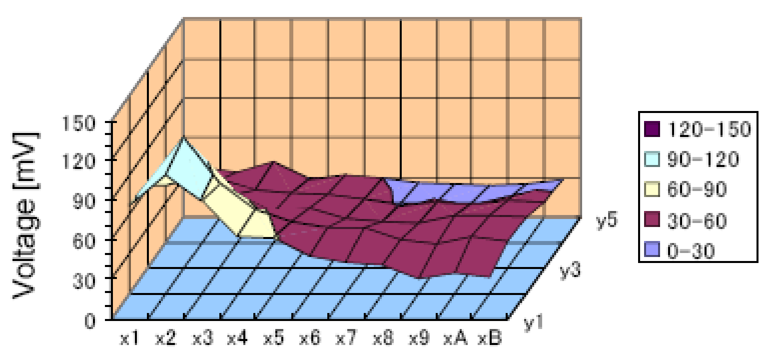
Fig.13 Measured voltage waveform between power/ ground planes



(a) H=200 um without global capacitors



(b) H=8um without global capacitors



(c) H=200 um with global capacitors

Fig.14 Measured power/ground bounce distribution in a whole board area

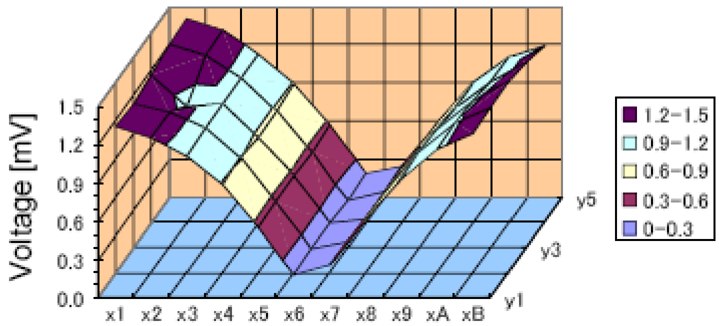


Fig.15 Measured power/ground bounce distribution at the first membrane resonant frequency $f_{(1,0)}$, 340 MHz

Conclusions

Electromagnetic radiations of 4-layer board with embedded decoupling capacitor composed of different insulator thicknesses were evaluated. In order to distinguish the effects of common mode radiation due to shoot-through current from the normal mode, radiated emission was compared for two lengths of signal traces on the different insulator thicknesses. It has been proved that common mode radiation due to shoot-through current was significantly reduced in a wide frequency range by the power bus structure with thinner insulators without any on-board global capacitors. On the other hand, on-board global capacitors were effective for reducing in a limited frequency range even in the case of a power bus with relatively thick insulators.

References

[1] T.H.Hubing, T.Van Doren, F.Sha, J.L.Drewniak, and M.Wihelm, "An Exprimental Investigation of 4-layer Printed Circuit Board Decoupling," Proc. of IEEE EMC Sympisium, Atlanta, GA, pp308-312, 1995.
[2] M.Xu, T.H.Hubing, J.Chen, T.P.Van Doren, J.L.Drewniak, and R.DuBroff, "Power Bus Decoupling with Embedded Capacitance in Printed Circuit Board Design," IEEE Trans. on EMC, vol.45, no.1, pp.22-30, Feb. 2003.
[3] H.Kim, B.K.Sun, and J.Kim "Suppression of GHz Range Power/Ground Inductive Impedance and Simultaneous Switching Noise Using Embedded Film Capacitors in Multilayer Package and PCB's," IEEE Microwave an Wireless Components Letters, vol.14, no.2, Feb. 2004.
[4] M.Swaminathan, J.Kim, I.Novak,and J.Libous, "Power Distribution Networks for System-on-Pacakage: Status and Challenges," IEEE Trans. On Advanced Packaging , vool.27, May 2004, pp.286-300.
[5] T.Fischer, M.Leone, and M.Albach, "An Analytical Model for Studying the Electromagnetic Radiation of Power-Bus Structures," Proc. of IEEE EMC Symposium, pp.225-230, 2003.
[6] J.Andersakis, T.Yamamoto, P.Pramnik, N.Biunno, "Design of Embedded Capacitors in PCBs and Organic Chip Packages using Ultra-thin Substrates," Proc. of DesignCon 2005.